

Multimode-Optical-Fiber Imaging Probe

Deborah Jackson

Jet Propulsion Laboratory

California Institute of Technology

Pasadena, CA 91109

ABSTRACT

Currently, endoscopic surgery uses single-mode fiber-bundles to obtain *in vivo* image information inside the orifices of the body. This limits their use to the larger natural orifices and to surgical procedures where there is plenty of room for manipulation. The knee joint, for example, can be easily viewed with a fiber optic viewer, but joints in the finger cannot. However, there are a host of smaller orifices where fiber endoscopy would play an important role if a cost effective fiber probe were developed with small enough dimensions (≤ 250 microns). Examples of beneficiaries of micro-endoscopes are the treatment of the Eustachian tube of the middle ear, the breast ducts, tear ducts, coronary arteries, fallopian tubes, as well as the treatment of salivary duct parotid disease, and the neuro endoscopy of the ventricles and spinal canal.

This work describes an approach for recovering images from tightly confined spaces using multimode. The concept draws upon earlier works that concentrated on image recovery after two-way transmission through a multimode fiber as well as work that demonstrated the recovery of images

after one-way transmission through a multimode fiber. Both relied on generating a phase conjugated wavefront, which was predistorted with the characteristics of the fiber. The approach described here also relies on generating a phase conjugated wavefront, but utilizes two fibers to capture the image at some intermediate point (accessible by the fibers, but which is otherwise visually inaccessible).

INTRODUCTION

Currently micro-endoscopes are needed for performing microsurgery in applications such as surgery finger joints, breast ducts, tear ducts, the fallopian tubes, coronary arteries, treatment of the Eustachian tube of the middle ear, and the neuro-endoscopy of the ventricles and spinal cord. The state-of-the-art micro-endoscope consists of 5000 single mode fibers bound together into a 0.5-millimeter diameter bundle. These bundles of single mode fibers are very fragile and break easily. At a cost of \$10,000 a piece, they are more expensive than the typical surgical procedure, hence are not cost effective viewers for most procedures.

In contrast, multi-mode fibers are considerably less expensive and much more mechanically robust. To date, they have not been used for surgical viewing because they scramble the phase information of the transmitted light such that the images are undecipherable. This paper presents a phase conjugate image recovery technique that should make affordable micro-endoscopes practical. It relies on the fact the one can capture the phase distortion imposed in an input beam resulting from fiber induced phase scrambling after propagation from point A_1 to point B_1 as is depicted in Figure 1.¹

That done, one can then create a beam which is predistorted with exactly the right initial phase information to allow the beam to backward propagate through the fiber in such a way as to unravel the phase distortion imposed by the fiber. The original wavefront is then recovered at point A_1 .

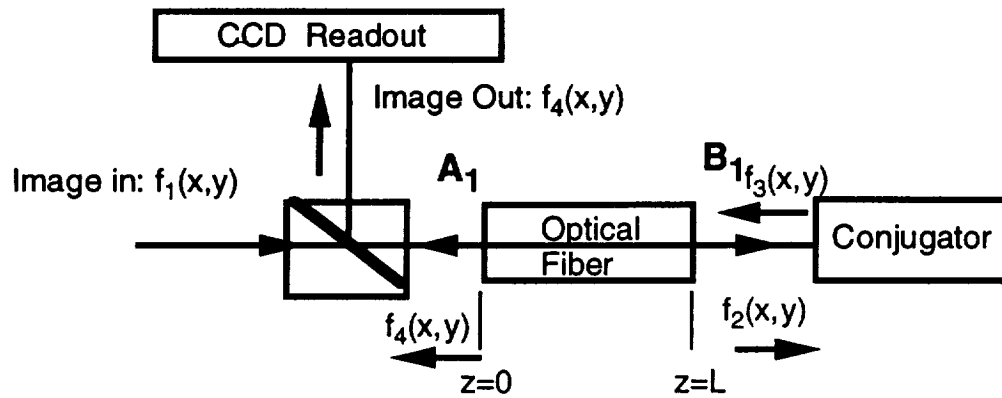


Figure 1. Image recovery after two-way transmission through a fiber.

A problem with this predistortion approach is that images injected at Point A_1 can only be recovered at A_1 . Thus with this scheme, it is not possible to move image information from a tightly confined space (say at point A_1) so that it can be viewed at point B_1 . Figure 2 depicts a double fiber setup, which allows one to inject an image at an intermediate point A_0 , between the end points B_0 and C_0 by use of a spliced pair of fibers. Use of the phase conjugating technique permits recovery of amplitude information from point A_0 , but to recover the phase information as well, one must place an optical ON/OFF micro-switch between the output of the fiber and the image sample.

The micro-switch has two operating states:

- ~100% reflection (OFF-state)
- ~100% transmission (ON-state)

One example of optical ON/OFF switch would entail mounting a piezoelectrically driven Fabry-Perot etalon at the output of the fiber. The piezoelectric spacer would then be used to scan the separation between the two-etalon mirrors so that the optical transmission and reflection states of operation are achieved simply by changing the spatial separation between the two mirrors.

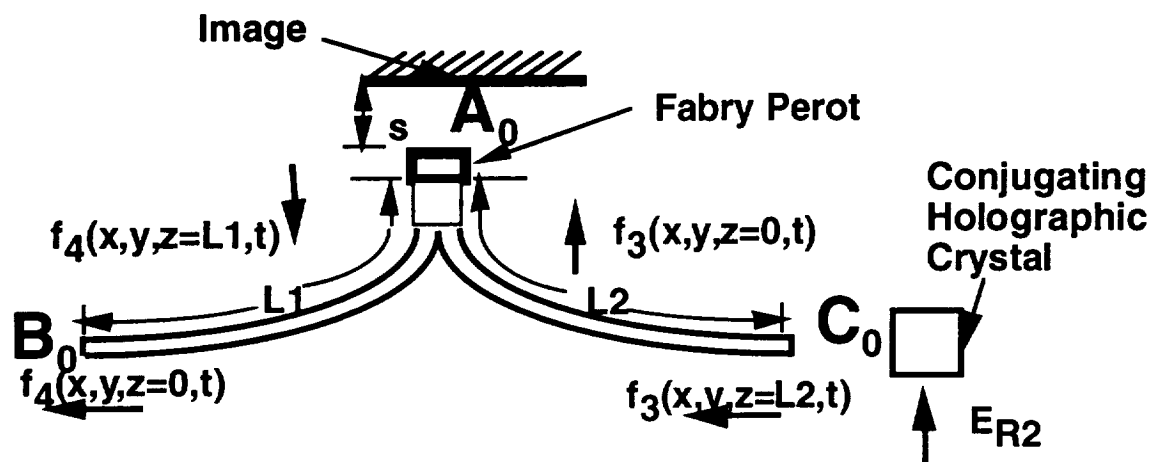


Figure 2. Setup for Remote Image Sampling with Fibers.

With the appropriate optical ON/OFF switch, the image recovery method utilizes the following steps:

- (1) Calibration of the fiber is performed with the optical switch at the image location, A_0 in the OFF state (~100% reflection).
- (2) The phase distortion information is concurrently recorded using a hologram at C_0 .
- (3) The optical ON/Off switch is placed in the ON state with ~100% transmission, so that the sample is illuminated.
- (4) The predistorted beam is injected into the fiber at point B_0 , samples the image at point A_0 , and is then viewed at point B_0 .

An analytical treatment of image propagation through such a spliced fiber² shows that the image information sampled at point A_0 exit at B_0 undistorted. In order for this method to work, it is assumed that the image is sampled in a time, τ_0 , which is short compared to the time photorefractive write/erasure time constant, τ , of the nonlinear crystal. Rhodium doped BaTiO₃ meets the above conditions. It takes several seconds for the holographic grating to form when writing at 532 nm wavelength with a hundred mWatts of optical power.

CONCLUSIONS

The two key technologies that are critical to recovering images from closely confined spaces with such a multimode fiber probe are:

(1) A nonlinear photorefractive crystal with appropriate time delays, (15 to 20 sec.).

(2) The development of an optical ON/OFF switch, which is easy to mount on to the end of a pair of fibers, joined as a Y-junction. From our preliminary analysis, MEMS Fabry-Perot interferometers are both compact enough and cost effective enough to satisfy the requirements for the optical switch in this application.

While the photorefractive crystals are now commercially available, the optical ON/OFF switch has yet to be developed.

REFERENCES

1. Volyar, A., Gnatovskii, A., Kukhtarev, N., and Lapaeva, S. "Image Transmission via a Multimode Fiber Assisted by Polarization Preserving Phase Conjugation in the Photorefractive Crystal", *Applied Physics B* **52**, (1991) 400-401.
2. Jackson, D.J., "Technique for Recovering Images from Tightly Confined Spaces", to be published in the *Journal of Optical Society of America, A* **16**, (1999).